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THE DESIGN, MANUFACTURE & TEST OF GOX FLOWMETERS

by

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I. INTRODUCTION

The objective of the work described in this report was to modify the design of a gaseous oxygen flowmeter (previously developed under Contract NAS8-2629) to new environmental and performance specifications and to fabricate and test 25 engineering models of the new design.

Changes in specifications included operation from 28V DC instead of 115V, 400 cycles, the incorporation of gain adjustments, the incorporation of a heater and insulation to allow operation to -155°C and an increase in the range of the instrument from 1000 to 1500 cc/min. These changes required the further development of a thermally controlled thermal shunt and a revised packaging arrangement.

The original instrument consisted of a preconditioning block, the detector, a power supply, gas fittings, electrical connectors and the housing. The preconditioning block consisted of a spiral of aluminum tubing soldered into the bottom of the housing.

From the preconditioning block the gas stream is directed onto the first of two heated thermocouples. Electrical response from the device is then obtained in the following manner: The two thermocouple units are made so similar in construction that when the electric heating currents are set to produce equal thermal EMF's in the two junctions at a given pressure, these EMF's will be equal at any pressure over a wide range for static (noflow) conditions. The two thermocouples are connected to buck such that the net output when at the same temperature is zero. The reference thermocouple is shielded from flow and the flow thermocouple is subjected to the cooling effects of the mass flow to be measured. Whereas, both thermocouples respond identically to environmental conditions, a net unbalance is produced by a mass flow through the unit. In the original device this unbalance was approximately 5mv at 1000 cc/min. flowrate. Figure 1 shows the configuration of the original unit.

II TECHNICAL FINDINGS

A. Power Supply

Since the unit developed under the original Contract (NAS8-2629) was designed to operate from 115V, 400 cycle power, an entirely new power supply was required to operate from the 28V DC now specified.

The circuit shown in Figure 2 was designed to provide the heater power for the thermocouples and the power for the temperature controlled heater to maintain the internal temperature of the device above -20°C.

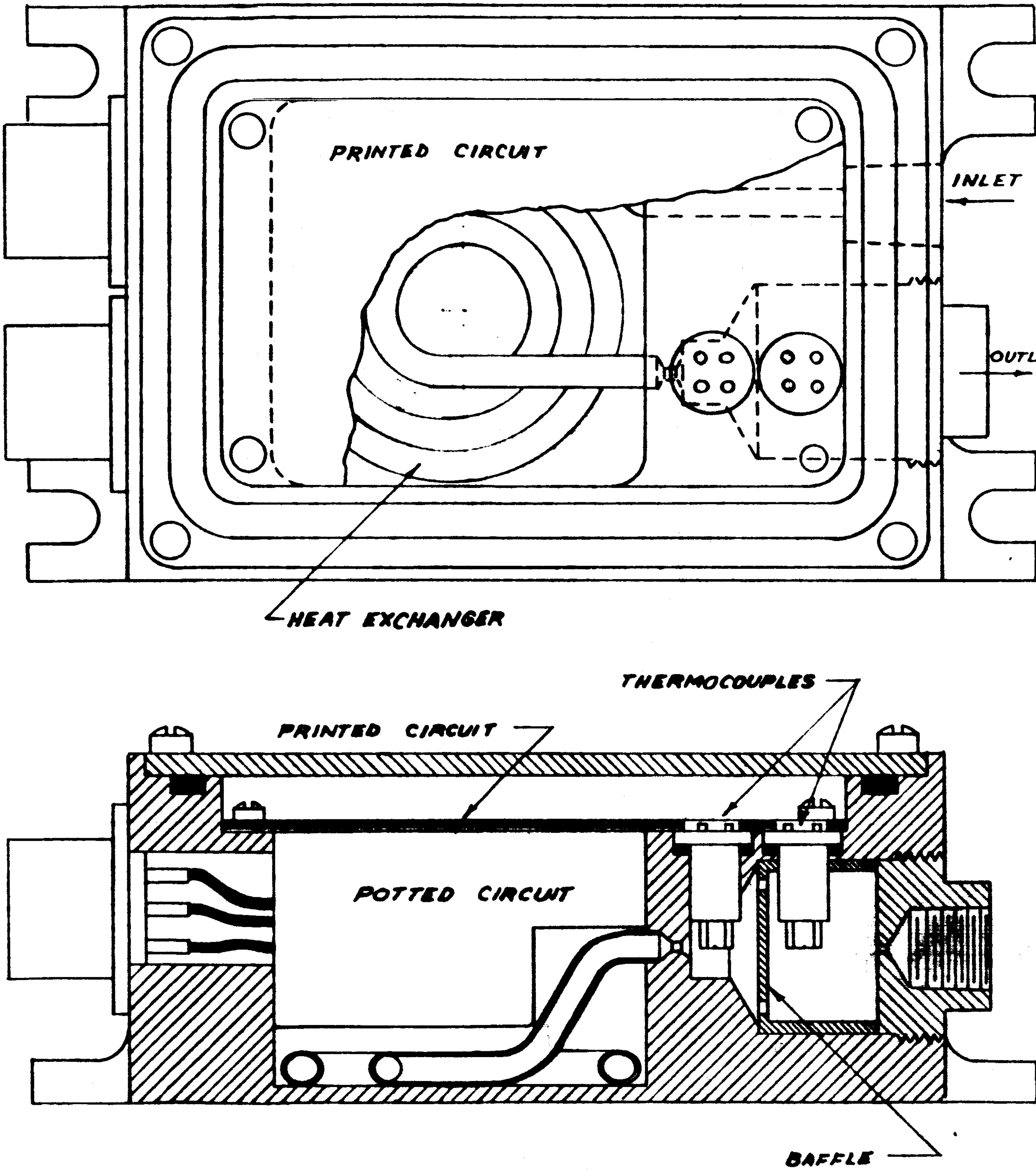
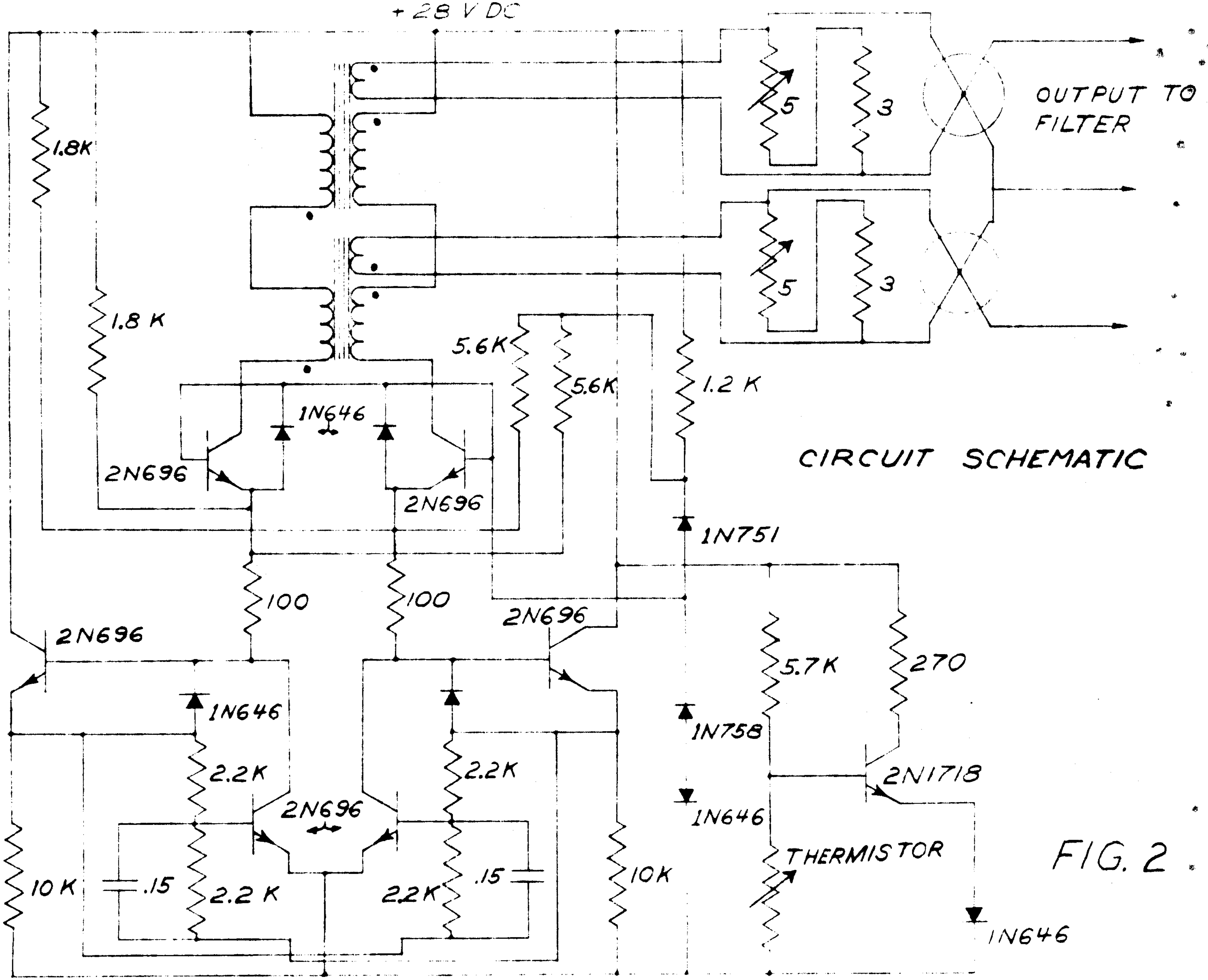


FIG. 1 EARLY CONFIGURATION



CIRCUIT SCHEMATIC

FIG. 2

The circuit consists of a free running multi-vibrator operating at a frequency of approximately four kilocycles which drives a push-pull grounded base amplifier which in turn delivers a constant current output of approximately 100 milliamperes RMS. Two output transformers are used with their primaries connected in series and their secondaries connected to the flow and static thermocouple heaters. Balance of the thermocouples is accomplished with adjustable resistances of 3 to 8 ohms which are in parallel with the thermocouple heaters. Reference for the constant current output is obtained with a 1N758 Zener diode in series with a 1N646 diode for temperature compensation. The output transformers have their primaries split into two equal sections to allow the direct current component of the input signal to be balanced out. The circuit draws 2.8 watts, not including the temperature controlled heater.

The transformers are wound on EI nickel-steel laminations. Comparisons made between the EI and ribbon wound toroidal core transformers showed no significant differences in operation. Precise measurements on EI and toroidal cores wound to the same D.C. resistance and turns ratio revealed a slightly lower leakage reactance on the toroidal core. Since they are larger than the EI cores, this was to be expected. Use of the EI cores resulted in the saving of considerable space in the unit with negligible effect on performance.

TABLE I

TRANSFORMER DATA

Core - 7/16" x 3/8" x 0.013" Nickel Steel EI Laminations, Stack of 11" x 0.013"

Core Center Leg Cross Section - 7/64" x .143"

Windings on Nylon Bobbin, window Area - 0.09" x 0.250" Wide

Winding #1, Primary - 500 T #38F, 56 Turns Per Layer

Insulation, Interwinding - 2 x 0.001" Mylar Tape, Thermosetting Adhesive.

Winding #2, Secondary - 25T #28F, 16 Turns 1st Layer, 9 Turns Second Layer

Outer Insulation - 2 x 0.001" Mylar Tape, Thermosetting Adhesive

Primary Leads - #26 Tinned Copper

Secondary Leads - #22 Tinned Copper

Units Vacuum Impregnated With Epoxy Resin

Signal Level, Primary - 4KC Square Wave, 10V RMS at .06 A RMS

Temperature compensation of the circuit is required between -20°C and 70°C. Using the output of the heated thermocouple as a detector, the power supply operations vs. temperature was measured over a somewhat greater range in order to detect any borderline operation. The results are shown in Table II.

TABLE II

Temp. °C	Thermocouple Output (Volts)
100	0.01152
90	0.01166
80	0.01181
70	0.01191
60	0.01196
50	0.01196
40	0.01195
30	0.01192
25	0.01190
0	0.01185
-10	0.01182
-20	0.01179
-30	0.01172
-40	0.01158
-50	0.01155

Voltage compensation is produced by a fixed resistor. With an output of 11.9 millivolts, the supply shows an increase in output of 0.1 millivolts for an increase of 3 volts in input voltage.

An RC filter was incorporated into the thermocouple output circuit. The filter is designed to reduce switching transient spikes and 4 KC thermocouple heater power on signal leads to a level of less than 20 microvolts.

The input signal level is not known accurately, therefore a filter design was arbitrarily set at a level that would suffice for signal levels somewhat above those measured.

The filter used consists of two 100 ohm series resistors and a 33 mfd. shunt capacitor. This gives an effective 200 ohms series resistance and at the heater fundamental frequency a shunt reactance of 1.21 ohms.

The ratio of these impedances is such that $E_{out}/E_{in} = -jXc/R$ with negligible error. At 4 Kc. E_{out}/E_{in} is $1.21/200 \cong 0.006$. For E_{out} of 20 uv., the allowable input is 3.3 mv. Measured values of E_{in} were in the 0.1 to 2 mv range, therefore the fundamental will be below 20 uv. Harmonics are of lower amplitude and the attenuation is much higher, therefore they are negligible.

A 1 microsecond (approximately) switching transient occurs every half cycle of the internal oscillator. The attenuation of the filter circuit as given by $E_{out} = (I_{in})(T)/C$ allows a pulse amplitude of 132 mv to be attenuated to 20 uv. In practice the transients on the signal leads were much less than this, however, inductive coupling from the internal oscillator to the leads in the connector produce some transient spikes which cannot be removed by an internal filter.

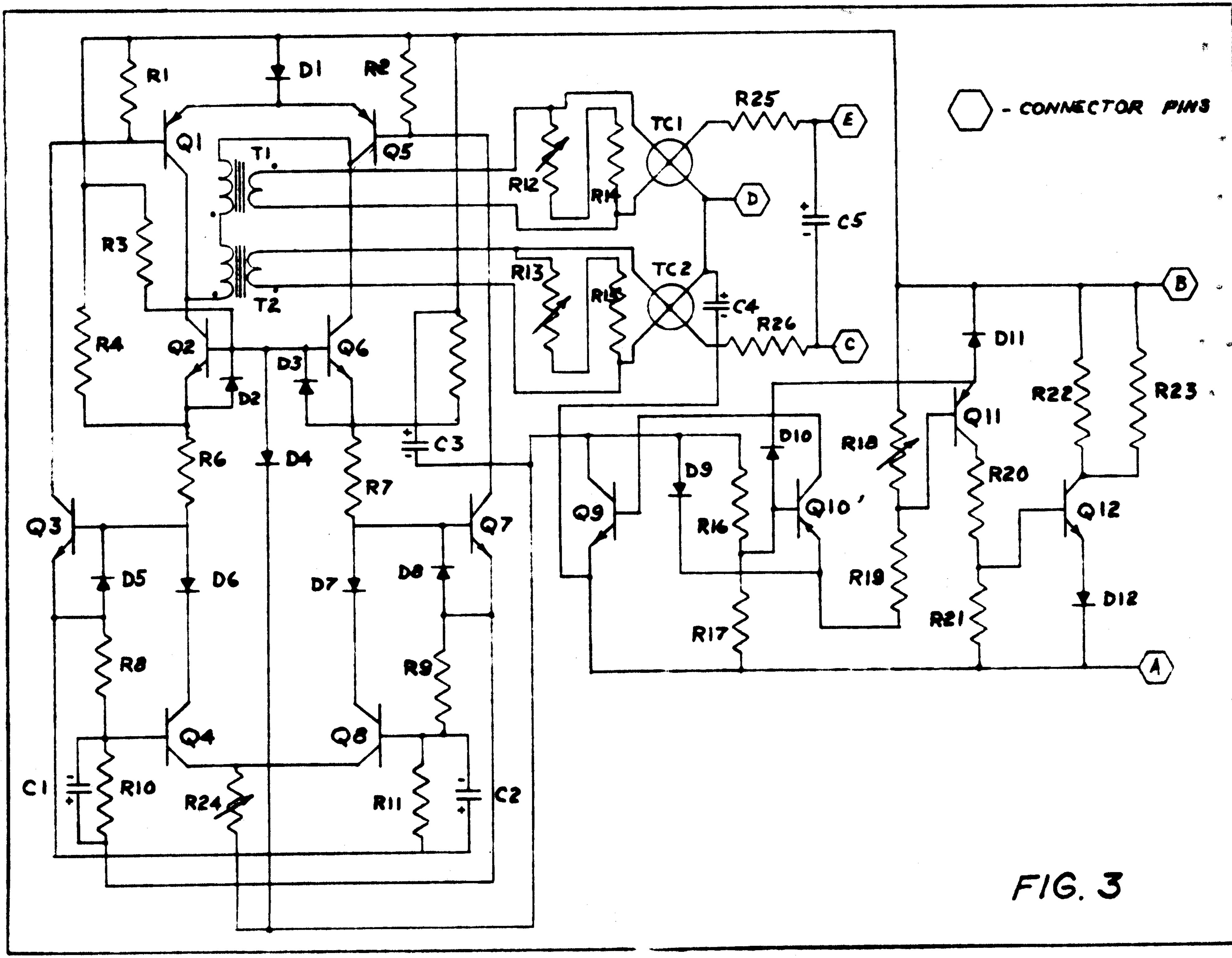
The input power required to operate the unit was subsequently reduced to 1.4 watts by reducing the reference voltage in the constant current regulator and by revising the circuit so as to eliminate the need for a center tapped primary on the output transformers. Some of the reduction in input power was forfeited when a sensitivity control was incorporated into the circuit. This control is R24 in the circuit diagram of Figure 3 and the associated parts list in Table III. Addition of this control allowed sensitivity adjustment without affecting the balance of the thermocouples established by R12 and R13. The circuit of Figure 3 was ultimately used in the engineering models.

B. Low Temperature Operation

The most severe change in the specifications of the unit was the reduction of the lowest environmental temperature at which it must operate to -155°C. To reduce the temperature compensation required in the power supply, and to avoid the wide temperature range the sensors would otherwise have to tolerate, the design objective was that the internal components would stay above -20°C under all environmental conditions.

From the size of the internal components and the complete package, it was obvious that both a high quality insulation and a secondary heat source would be required to maintain the instrument above -20°C internally at an ambient of -155°C.

An investigation of possible insulating materials lead to the selection of Styrofoam 22 (Dow Chemical) and APCO #1414 (Applied Plastics Co., Inc.) as suitable and showing negligible difference in



R1
D1
R2
Q1
Q5
T1
T2
R3
R4
Q2
D2
D3
Q6
R6
D4
R7
C3
Q3
Q7
D5
D6
D7
D8
R8
R9
Q4
Q8
C1
R10
R24
R11
C2
R12
R14
TC1
R25
E
D
C5
R13
R15
TC2
C4
R26
C
- CONNECTOR PINS
B
D11
R22
R23
Q11
R18
D10
D9
R20
Q9
R16
Q10'
Q12
R19
D12
R17
R21
A

FIG. 3

insulating properties as employed here. The insulation is available either pre-foamed or foamed-in-place. In this unit the insulation was always foamed-in-place because of the significant improvement in mechanical rigidity of the completed package over that obtainable with pre-foamed slabs. Table IV lists the important physical characteristics of the materials considered with Teflon included for comparison.

TABLE IV

MATERIAL	DENSITY	MANUFACTURER	THERMAL CONDUCTIVITY - (@-155°C) $\frac{\text{BTU-IN}}{\text{Ft}^2\text{-Hr-}^\circ\text{F}}$
Styrofoam 33		Dow Chemical Co.	.11
Styrofoam 22		Dow Chemical Co.	.09
APCO 1414		Hexcell Products Inc.	.09
Sta Foam AA-402	2#/Ft^3	American Latex Corp.	.105
Polycel 440	4#/Ft^3	Polytron Corp.	.10
PAPI-1008	3#/Ft^3	Carwin Corp.	.11
Teflon		E.I. DuPont de Nemours	.75

Figure 4 shows typical data obtained in insulation tests. These data were taken with a solid aluminum inner block with a resistance heater to mock up the instrument and an outer box having the same dimensions as the final housing. These data finally proved to yield too low a heater power by almost a factor of 2. The greater heater power requirement than predicted here resulted from inner package

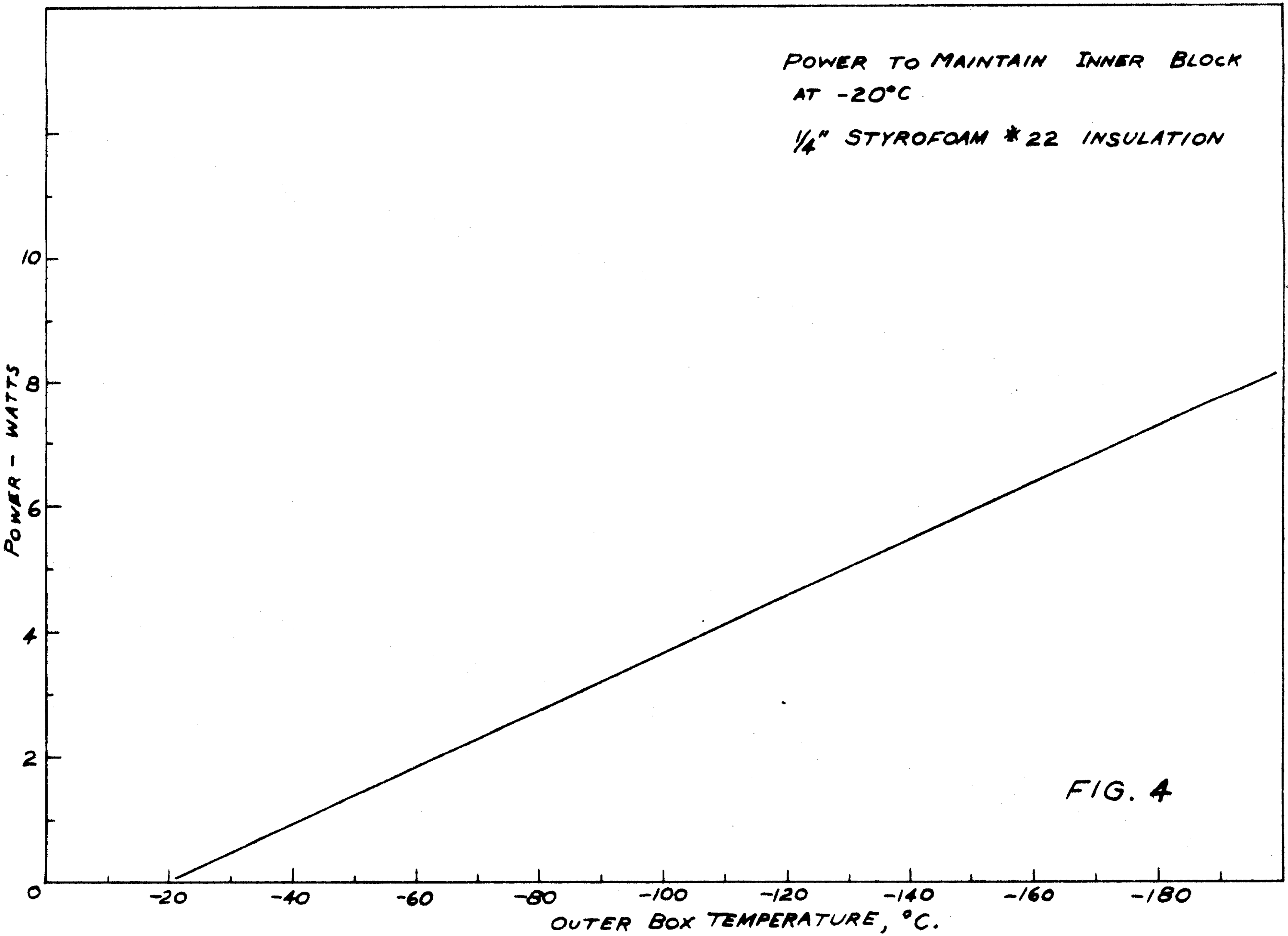

POWER TO MAINTAIN INNER BLOCK
AT -20°C
1/4" STYROFOAM *22 INSULATION
POWER - WATTS
0
2
4
6
8
10
-20
-40
-60
-80
-100
-120
-140
-160
-180
OUTER BOX TEMPERATURE, °C.

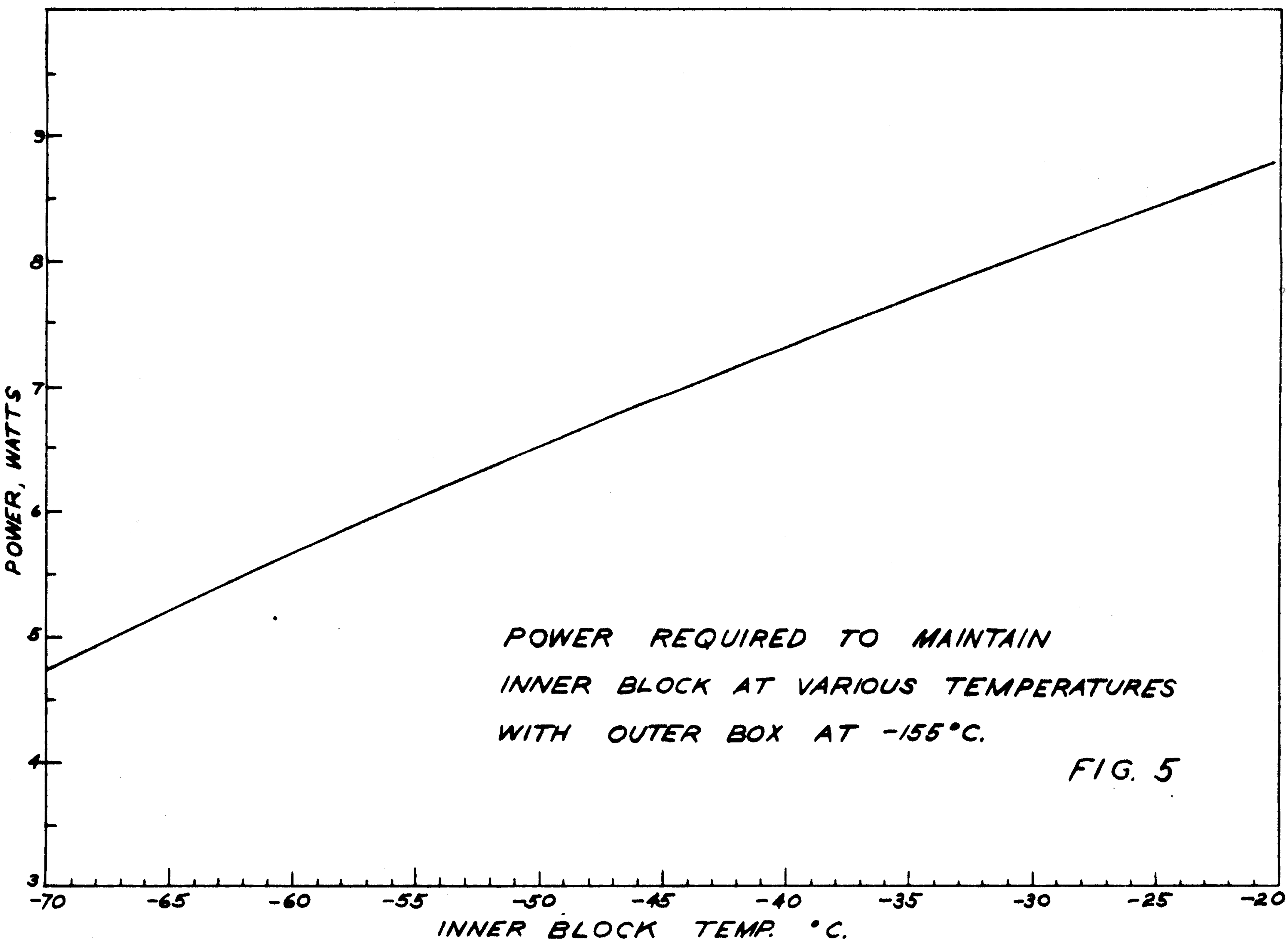
FIG. 4

surface irregularites, poor insulating properties of the end seals, the inward protruding electrical connector (which was not available when the tests were conducted) and the rerouting of electrical conductors between the housing and the inner package. The tests were of value, however, for comparing the properties of various insulators under the same conditions.

Data taken on later mockups, which were very similar to the final unit, yielded results as shown in Figure 5.

The heater control and the heater are shown in Figure 3 as transistors Q11 and Q12, with their associated components. R18 is a thermistor to sense the temperature of the inner block and R22 and R23 are the heaters. Component values are selected such that the heater power is full on at -20°C and off at about -10°C.

Since the inner package is insulated from ambient and in operation is dissipating at least 1.4 watts, the temperature can rise above ambient in the inner package. With ambient at 70°C, measurements indicate that the temperature of the inner package will not exceed 100°C. In order to restrict the possible range of temperature variation to which the inner package is exposed, provisions are made to thermally connect the inner package to the housing when the temperature of the inner package exceeds about 20°C. Below this temperature the thermal connection is broken. The thermal connection, or shunt,



POWER REQUIRED TO MAINTAIN INNER BLOCK AT VARIOUS TEMPERATURES WITH OUTER BOX AT -155°C.

FIG. 5

is accomplished with a 1/4 inch Freon -12 filled bellows mounted to the inner package and guided so that it can make contact with the bottom of the housing at elevated temperatures. With the thermal shunt, the inner package temperature tracks ambient temperature within about 2^{o}C. at higher temperatures.

C. Vibration Sensitivity

Vibration sensitivity in the device can result from oscillatory motion in the gas relative to the thermocouple junctions. The junctions have been shown to be rigid with respect to the machined passageways in the unit. Other components in the flow paths however, can under vibration produce a pumping action on the gas in the unit and thus cause a response. The heat exchanger insert, inlet orifice or baffle can potentially produce the pumping action. In the early experimental models, wherein the orifice and heat exchanger insert were held in place by Teflon and Neoprene under compression, vibration sensitivity attributable to these components was observed. These sources were subsequently eliminated by shrink fitting these components into their respective passageways.

During the vibration tests, it was observed that the motion of flexible connecting lines, relative to the unit under test, could also produce a pumping action. This effect was confined to the exit line since the flow impedance was sufficient at the inlet to damp the oscillations.

The effect at the exit was made negligible by the addition of a baffle to protect the reference junction from the direct action of the exit orifice.

D. Response Characteristics

Shock waves or oscillations produced in the heat exchanger, or about the inlet of the flowmeter, produced excessive cooling of the flow thermocouple at certain flow rates. This same effect had occurred in the original unit developed under NAS8-2629 but was restricted to flow rates above the intended range of the instrument. In the present instrument, the anomalies fell between 700 and about 1300 cc/min. The exact source of the oscillations was never located. The effect was satisfactorily suppressed, however, by the incorporation of a filter network into the inlet orifice. The filter consists of an impedance followed by a cavity, followed by another impedance. This is the equivalent of an electrical RC filter network wherein the last impedance is the inlet orifice. A typical response curve of a unit is shown in Figure 6.

E. Revised Packaging

The increase in the number of electrical components and the requirement for thermal insulation between the inner package and the housing resulted in a complete revision of the unit package. Figure 7 shows the new package.

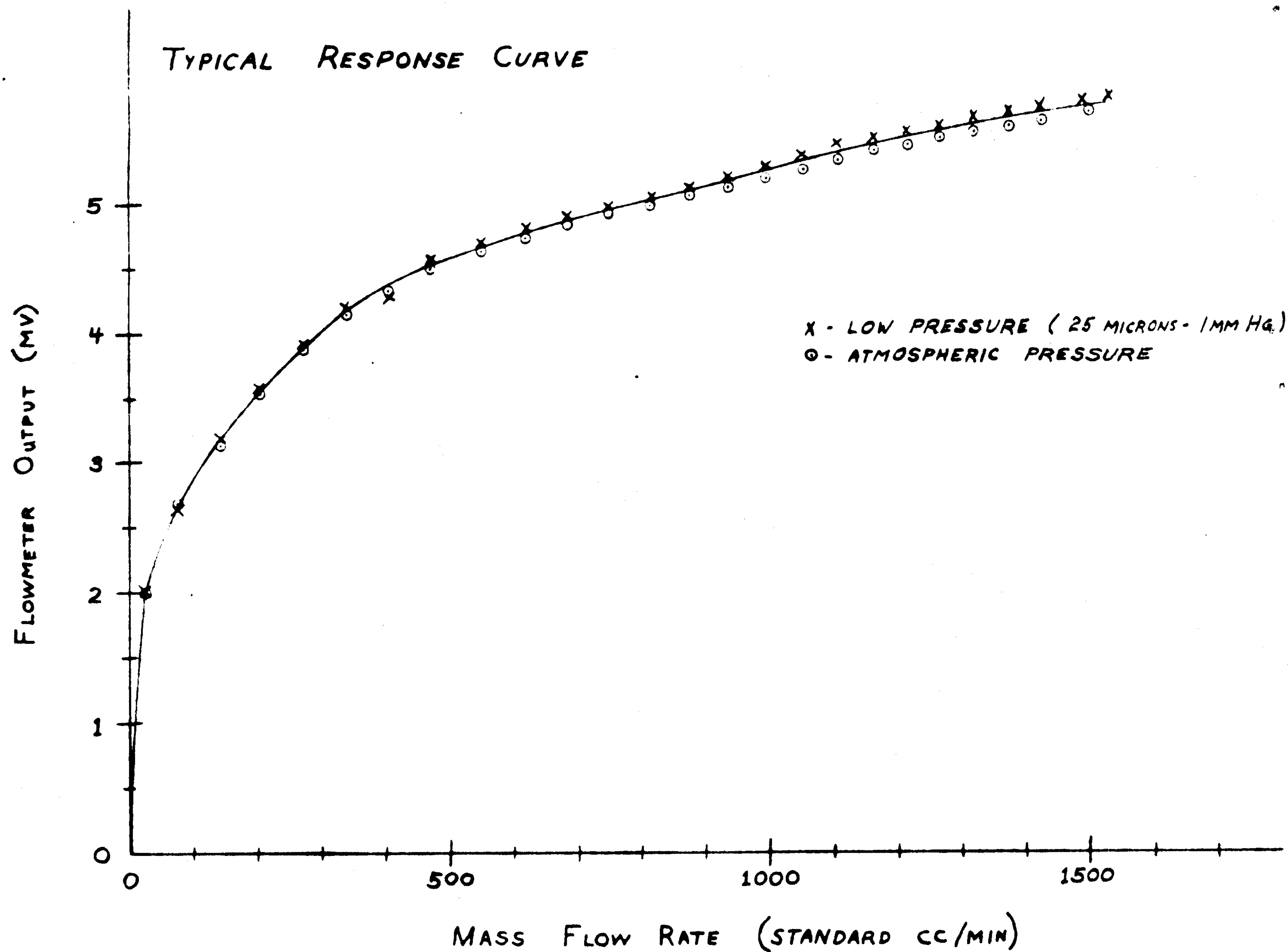

TYPICAL RESPONSE CURVE
X - LOW PRESSURE (25 MICRONS - 1MM HG)
⊙ - ATMOSPHERIC PRESSURE
FLOWMETER OUTPUT (MV)
0
1
2
3
4
5
0
500
1000
1500
MASS FLOW RATE (STANDARD CC/MIN)

FIG. 6

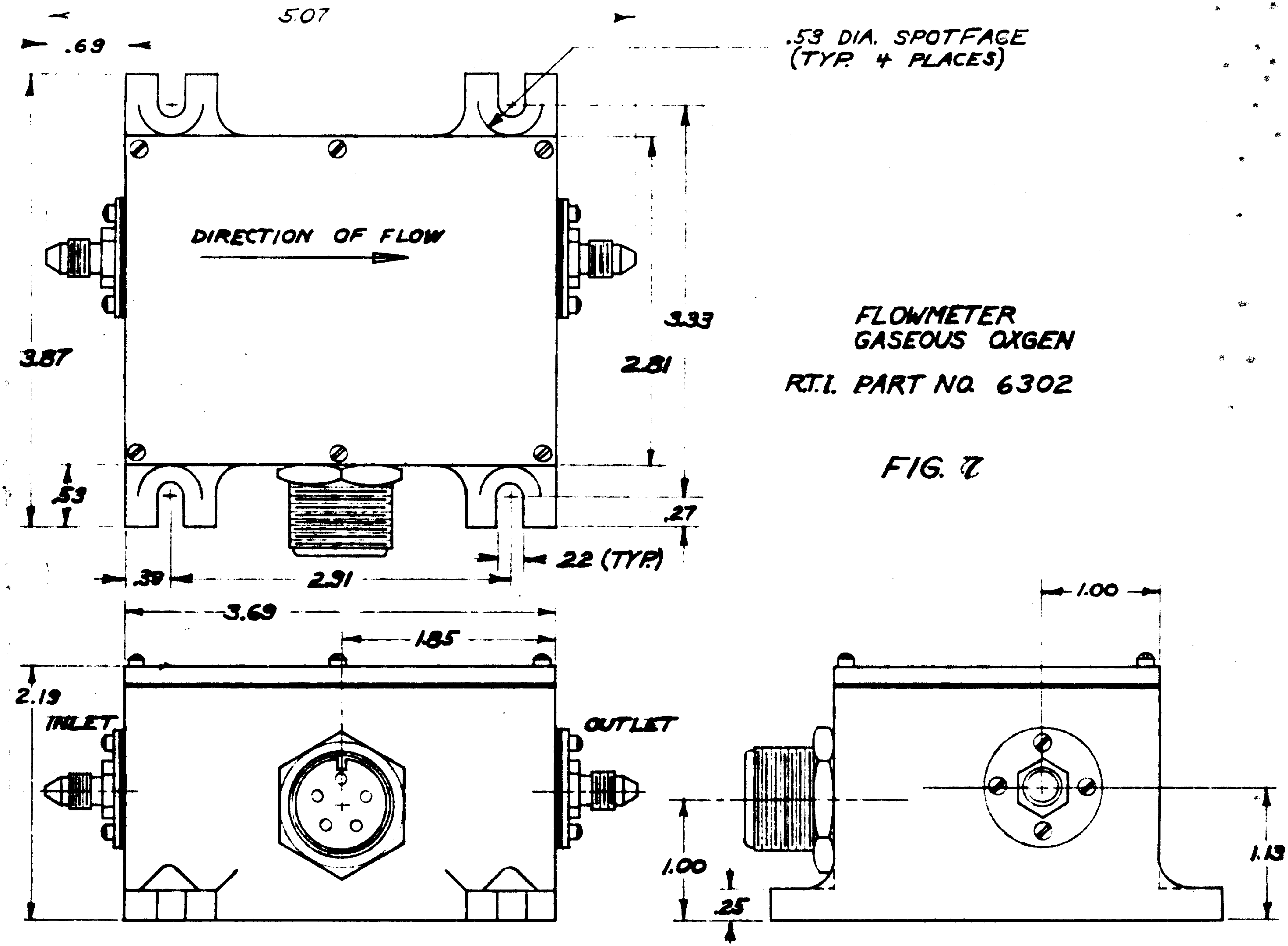

5.07
.69
.53 DIA. SPOTFACE
(TYP. 4 PLACES)
DIRECTION OF FLOW
3.33
3.87
2.81
.53
.27
.22 (TYP.)
.38
2.91
3.69
1.85
1.00
2.19
INLET
OUTLET
1.00
.25
1.13
FLOWMETER
GASEOUS OXGEN
R.T.I. PART NO. 6302

FIG. 7

III EVALUATION OF RESULTS

The program resulted in the design of a gaseous oxygen flowmeter meeting the requirements of the specifications. The detailed specifications are listed in Table V.

IV PRODUCTION

Twenty-five engineering models of the flowmeter were fabricated and tested under the contract. Construction was straightforward considering the complexity and compactness of the device. Very minor difficulties were encountered with component reliability with the exception of the trimpots. The trimpots were largely faulty on delivery and the vendor was slow to recognize and correct the faults. The faults in the trimpots were excessive and variable slider contact resistance and unreliable clutch operation.

All production units of the flowmeter were subjected to final inspection and test. Listed below in A is the equipment used and in B the test procedures in brief form.

A. Equipment Used

Recorder, 0-10 millivolt, Varian G-14 calibrated with Rubicon potentiometer having internal Weston Standard Cell.

Reference Flowmeter, Brooks "150", Calibrated by timed displacement of known volume of water.

TABLE V

1. Scope - The leak meter is designed to measure gaseous oxygen leak rates from flanges in the liquid oxygen plumbing systems of a space vehicle.

2. Input Signal - Gaseous oxygen flow of 0 to 1500 standard cubic centimeters per minute, at temperatures from $-180^{\circ}C$ to $+ 75^{\circ}C$.

3. Output Signal - The output from the leak meter shall be 0 to 5.7 millivolts plus or minus 0.2 mv for flow rates of 0 to 1500 std. cc/min.

4. Response Time Constant - With a sudden application or removal of 1500 cc/min. flow rate, 63.2% of the total output change shall occur in less than 0.2 seconds.

5. Calibration - Each leak meter shall be calibrated at 100 std. cc/min. intervals from 0 to 1500 cc/min. accurate to 0.5% of flow rate.

6. Power Supply - The leak meter will operate from 28V DC plus or minus 3 volts and will dissipate 1.7 to 10.0 watts after warm-up, depending on the ambient temperature.

7. Accuracy - The leak meter shall measure gaseous oxygen flow rates over the specified range with an accuracy of plus or minus 5% in the electrical output signal. This accuracy will be maintained while the meter is subjected to any one or all of the environmental conditions set forth in 8 through 14.

8. Ambient Temperature - The leak meter will be subject to ambient temperatures from $-155^{\circ}C$ to plus $75^{\circ}C$.

9. Vibration - The leak meter shall operate properly during and after vibration to the following levels 10-40 cps at 0.25 double amplitude displacement 40-2000 cps at 35 G's with a sine wave excitation.

10. Altitude - The leak meter shall maintain the specified accuracy while subjected to ambient pressures from 760 to 10^{-5} millimeters of mercury.

11. Moisture - The leak meter shall be protected against relative humidity up to 100.

12. Fungus - The construction materials will resist any type of fungus growth.

13. Shock - The leak meter shall operate properly after subjection to a shock of 50 G's for a period of 10 millisecond duration. The shock wave shape shall be that of a half sine wave.

14. Acceleration - The leak meter shall operate properly after subjection to an acceleration of 10 G's for a duration of 5 minutes.

Manometer, Hg, standard corrections applied as required

Variable D.C. Power Supply, H. P. Model 712 A

Voltmeter, 50 volt scale of RCA WV-38A, calibrated with 1% voltage divider against Rubicon potentiometer having internal Weston Standard Cell.

Low Pressure Chamber, custom high vacuum system, monitored with two T/C gauges and an ionization gauge.

Low Temperature Chamber, foam insulated box, cooled with dry ice or LN_2, temperature monitor - Chromel Const. T/C, calibration checked at dry ice and LN_2 temperatures.

Oven, Thelco Model 18, temperature monitor - Simpson Model 388 checked against 2 Hg thermometers.

Oxygen supply tank, regulator and control valves.

B. Test Procedures

Test #1 - Sensitivity

Connect the unit under test to the D.C. power supply and set for 28 volts. Connect the oxygen supply to the inlet and the reference flowmeter to the outlet. Connect the common lead from the thermocouples (pin D) to the negative terminal of the recorder and the lead from the reference thermocouple (pin E) to the positive terminal of the recorder. Then with no flow through the unit adjust R12 to produce 8 millivolts output from the thermocouple. Disconnect the common lead (pin D) from the negative terminal of the recorder and connect the output of the flow sensing thermocouple (pin C). Adjust R13 such that the net output of the two bucked thermocouples in zero as observed on the recorder. Establish a flowrate of 1500 cc/min. through the unit as observed on the reference flowmeter and adjust R24 to produce an output reading on the recorder of 5.7 plus or minus .2 millivolts. Read and record the millivolts out at 100 cc/min. intervals from 0 to 1500 cc/min.

Test #2 - Pressure Drop

Insert T connections at the inlet and outlet of the unit under test and connect either side of a Hg manometer to the Ts. Establish a flow rate of 1500 cc/min. through the unit and observe the displacement of the Hg in the manometer. Net displacement must be less than about 40 cm Hg.

Test #3 - Voltage Regulation

With the flowrate through the unit at 1500 cc/min. read and record the output at 25, 28 and 31V DC input voltage. Maximum variation in output is plus or minus 0.2 millivolts.

Test #4 - Low Temperature Operation

Lower outer case temperature of unit to -155°C while monitoring the current drag of the unit. When the current rises sharply and levels off at a high value, observe and record output at 1500 cc/min. flowrate. The output at -155°C must be within plus or minus 0.2 mv of 20°C output.

Test #5 - High Temperature Operation

Connect unit as in Test #1 with unit in oven at 75°C. Allow unit to operate 1 hour to establish temperature equilibrium and measure output at 75°C. The output at 75°C must be within plus or minus 0.2 mv of output at 20°C.

Test #6 - Low Pressure Operation

The unit is placed in a vacuum chamber with a continuous line connected through the chamber to the inlet to supply oxygen. The outlet dumps into the vacuum chamber. The vacuum chamber is evacuated and with the unit operating but zero gas flow the balance at low pressure is observed. Measurable changes occur above about 300 u Hg if at all. However, evacuation to about 25 u Hg is rapid with only a mechanical pump and the check is normally carried out at this pressure. The change in balance between atmospheric pressure and 25 u Hg should not exceed plus or minus 0.05 mv.

With the system at low pressure, the reference flowmeter is connected to the exhaust of the pumping system. If the system is tight, the reference flowmeter will accurately measure the flowrate through the unit under test. Read and record the output signal at 100 cc/min. intervals from 0 to 1500 cc/min. With a 375 liter/min. pump the system pressure will rise to about 1 mm Hg at full flow rate. The output at full flow at low pressure must be within plus or minus 0.2 millivolts of the output at full flow at atmospheric pressure.

Test #7 - Leaks

With the outlet of the unit plugged, connect the source of oxygen and the manometer to the inlet of the unit. The entire system should have a nominal volume of 60 cc. Raise the system pressure above 50 cm Hg and close off the system. The pressure in the system should drop less than 0.1 cm Hg in 5 minutes.

V CONCLUSIONS & RECOMMENDATIONS

The unit as designed seems highly satisfactory for the intended use. Two suggestions are put forward, however, which if pursued might lead to significant cost reductions and improved reliability. First, the temperature rise in the unit when operated at high ambient temperature is not as great as anticipated. Therefore, it seems quite likely that the thermal shunt could be safely eliminated. Elimination of the thermal shunt saves the cost of the several parts that must be fabricated, assembled and tested and improves the thermal insulation of the inner package. A greater saving would result from the simplification of the final assembly of the flowmeter which must presently be done at low temperature to avoid damage to the thermal shunt. Secondly, a long term experimental reliability program should be conducted to evaluate the effect of eliminating the thermal shunt as well as shelf-life, standby operation and possible long term extreme environmental effects on the instrument.